Escape Effect of Secondary Electron Bremsstrahlung

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When a solid target is bombarded with heavy charged particles, continuous X rays, in addition to characteristic X rays, are produced. As the background of the characteristic X-ray peak, these continuous X rays are an important factor to determine the detection limit of PIXE. The continuous X rays are considered to be secondary-electron bremsstrahlung (SEB), Radiative electron capture (REC), quasifree-electron bremsstrahlung (QFEB), nuclear bremsstrahlung (NB) and Compton Scattered-γ rays from nuclear reactions. Among these, SEB is usually most predominant in the bombarding energy region for PIXE. SEB is the bremsstrahlung which is produced by close collisions between a target nucleus and a secondary electron ejected by projectiles. SEB has been well studied by Folkmann et al.[1] and by Ishii et al.[2] It has been theoretically known that the intensity of SEB is not proportional to the target thickness because of the escape effect, which means that a secondary electron produced in the target can escape out from the target before producing the bremsstrahlung if the range of the electron is larger than the path length in the target. This effect results in a reduction of SEB intensity, and is expected to give rise to high sensitivity of PIXE, while it has not yet been studied. Here, the target-thickness dependence of SEB is measured and the experimental result is discussed in comparison with the theoretical calculation of the escape effect.

The production process of SEB is schematically shown in fig. 1, where $R(E_e)$ is the range of an ejected electron. If $R(E_e)$ is related to the path d of the ejected electron in the target by

$$R(E_e) \geq d + R(h\omega) ,$$

the electron can escape out from the target before producing the bremsstrahlung of energy $h\omega$ and does not contribute to the production of SEB. In a case of thick target comparing with $R(E_e)$, this effect is considered to be negligible. The electron range in Mylar is estimated from that in Al[2] to be

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$$R(E_e) = 1.98\ E_e^{\ 2}\ \mu g/cm^2 \quad (E_e \text{ in keV}).$$

The maximum energy of ejected electrons is approximately given by $T_m = 4\ E_p\ m_e/m_p$, where E_p, m_e, and m_p are, respectively, the projectile energy, the electron mass and the proton mass: the maximum energy that can be transferred from the projectile to a free electron. From the above equation, the range $R(T_m)$ is 2.5 μm for 6-MeV protons. Mylar foils of 10- and 40-μm thickness are therefore regarded as thick enough and the escape effect can be neglected. The X-ray spectra for 10- and 40-μm Mylar foils bombarded with 6-MeV protons were measured at $\theta_L = 43.5°$ and 130° and are shown in fig. 2, where no difference in the spectrum is found between the 10- and 40-μm Mylar foils. On the other hand, the range $R(T_m)$ of 20-MeV protons is 27 μm. The production cross section of SEB for 20-MeV protons are shown for 4-, 10- and 40-μm Mylar foils in fig. 3, where the cross section clearly decreases with a decrease in the target thickness, i.e., the escape effect. Recently[3], we have derived a formula for the SEB production taking into account the escape effect. Using this formula, the effect for a Mylar target was calculated as a function of the target thickness and the results are shown in fig. 4 together with the experimental results. Both the experimental and theoretical values are shown by the ratios to the cross section for the 40-μm Mylar foil and $\theta_L = 148°$ at $\hbar\omega = 14$ keV. Agreement between the calculation and the experiment is quite satisfactory; by taking the target thickness into consideration, we are capable of reducing the SEB background and improving the detection limit. In case of low-energy projectile, however, the maximum energy of the ejected electrons T_m is small and the range $R(T_m)$ is also small. Hence, in order to take advantage of the escape effect, an extremely thin target might be needed. Further, the characteristic X-ray production cross section generally decreases with a decrease in the projectile energy, though the SEB production cross section decreases. Hence, it seems to be difficult to improve the detection limit for low-energy projectiles by taking advantage of the escape effect. On the other hand, the production cross section for characteristic X rays and also the range of ejected electrons increase with an increase in the projectile energy, and we can suppress the increase in the intensity of SEB by means of the escape effect. By taking advantage of the escape effect, thus, the PIXE sensitivity can be improved for high-energy-proton bombardments.

References

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3) Yamadera A., Ishii, K., Sera K., Sebata M. and Morita S., Phys. Rev. A <u>23</u> (1981) 24.

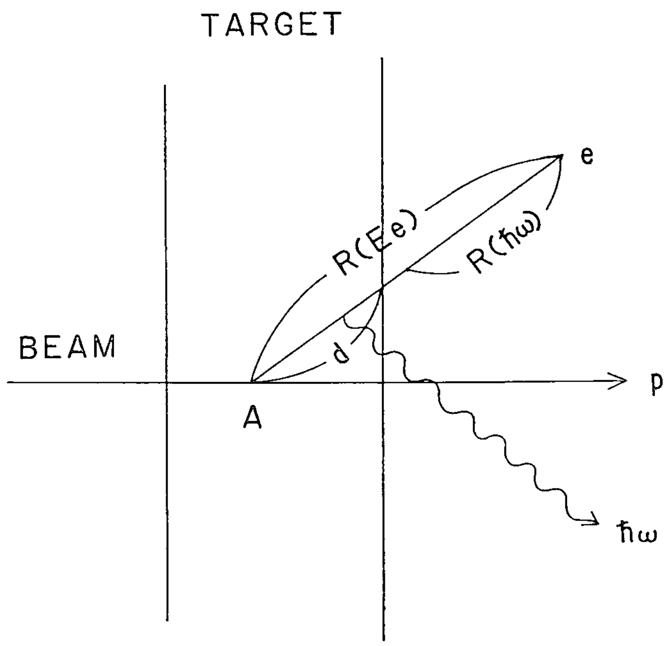

Fig. 1. An incident proton ejects an electron of energy E_ε at point A, and the electron loses its energy in passing through the target material. If the electron escapes out from the target with an energy larger than the X-ray energy $\hbar\omega$, the electron does not contribute to the production of SEB lower than $\hbar\omega$.

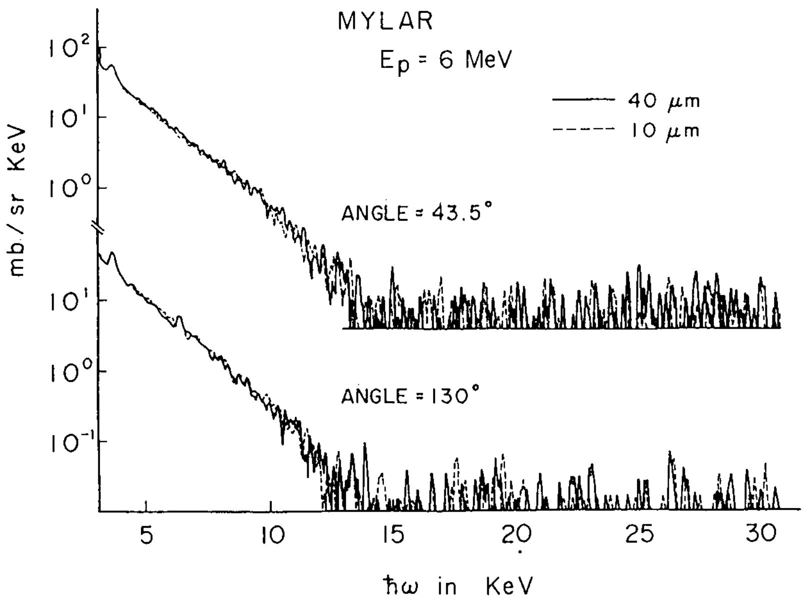

Fig. 2. Continuum X-ray spectra for 10- and 40-μm Mylar foils bombarded with 6-MeV protons. Since the target thickness is large enough in comparison with the range of ejected electrons, no escape effect can be recognized.

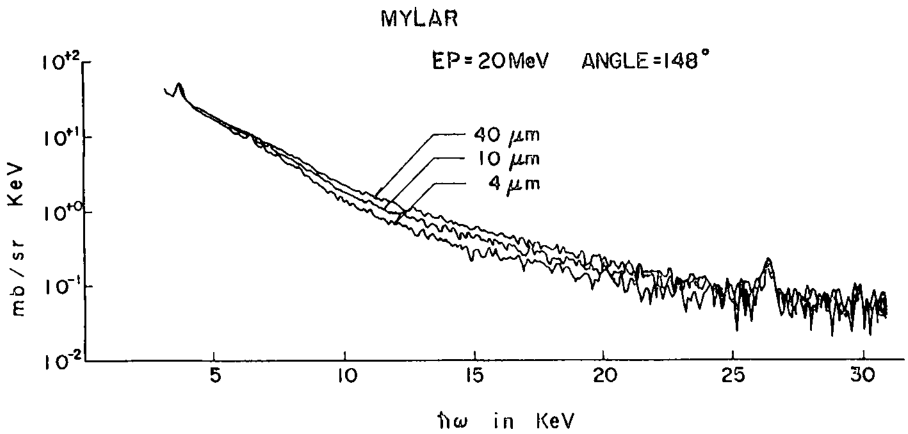

Fig. 3. Continuum X-ray spectra for 4-, 10-, and 40-μm Mylar foils bombarded with 20-MeV protons. The escape effect is clearly found.

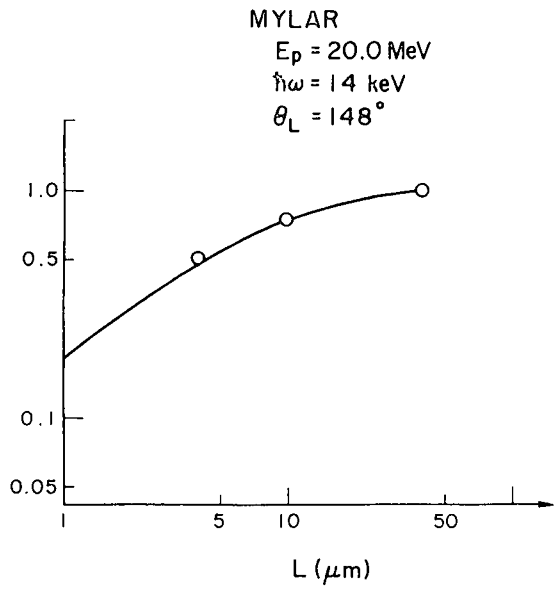

Fig. 4. The escape effect on SEB produced by 20-MeV-proton bombardments is shown as a function of thickness of the Mylar-foil target. The solid line is calculated from the formula given in Ref. 3. Both the calculated and the experimental cross sections are normalized to those for the 40-μm Mylar.